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THE OAHU EARTHQUAKE OF JUNE 1948, ASSOCIATED SHOCKS, AND THE HYPOTHETICAL DIAMOND HEAD FAULT

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ABSTRACT

Contemporary and later reports on the Hawaiian earthquakes of late June 1948 indicate that the most significant earthquake of the period occurred at 10:41 (HST, equivalent to 11:41 GMT) on 28 June. The highest intensities of this earthquake were on Oahu--those at Honolulu averaging VI on the Modified Mercalli scale and reaching VII on Tantalus and in Iwilei. Its intensity distribution suggests that the earthquake had a Richter magnitude of 4.8+/-0.5, an epicenter within 50 km of 21.2° N, 157.90° W (just offshore from Honolulu), and a focal depth of less than 20 km and probably only about 5 km. Considering its intensity distribution and probable epicenteral location, it is appropriately identified as the Oahu earthquake of 1948.

The earthquake may have been preceded by an unfelt foreshock at about 01:38 and followed by an aftershock felt in Honolulu at about 01.51. A quake felt on Oahu at 19:32 on 17 January 1948 may have been an additional foreshock.

The estimated epicenter of the principal shock falls on the trend of the hypothetical Diamond Head fault, whose existence was originally suggested on the basis of the alignment of seven earthquakes occuring the the period from 1962 through 1977. Two more earthquakes occurring in 1981 had epicenters on the fault line; and two occurring in 1976 probably did. As many as 31 earthquakes felt on Oahu in the period from 1859 through 1983, including the June 1948 earthquake and its possible January foreshock and June aftershock, originated, or might have originated, on the hypothetical fault.

Although there is clearly a preferential distribution of earthquake epicenters along the hypothetical fault zone, the preference is no greater than that along some other zones in the general area that have not been identified as faults; there is no other geological or geophysical evidence of the existence of the fault, and only very slight bathymetric evidence. Neither the frequency distribution of the magnitudes of the earthquakes that originated or might have originated on the trend of the hypothetical fault nor the frequency distribution of the Honolulu intensities of those earthquakes suggest the existence of a seismic gap along that trend.

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INTRODUCTION

Impetus to study

Among historic earthquakes, that occurring on 28 June 1948 probably had the second highest intensities on Oahu. The highest intensities were those of an earthquake centered at or near Lanai that occurred in February 1871. That earlier earthquake and the June 1948 earthquake are obviously of special interest in the investigation by a Task Force that has been established by the Natural Hazards Group of the University of Hawaii to investigate the question of the seismic risk zone to which Oahu should be assigned. This report on the June 1948 earthquake and shocks asssociated with it has been prepared as a contribution to that investigation.

The Oahu intensities of historic earthquakes in general will be the subject of a separate report (Cox, in press a), and a special report on the Lanai earthquake of 1871 has already been prepared (Cox, 1985a). The preparation of another special report on the June 1948 earthquake and shocks associated with it is stimulated, not only by its high Oahu intensities, but by the fact that, although they occurred just over a quarter of a century ago when there were seismographs on both Oahu and Hawaii, there are inconsistencies in the reported numbers and times of the shocks and in the epicentral location of the principal shock, and the magnitude of the principal shock seems not to have been estimated.

In the study reported here, the principal concern was with the intensity distribution of the earthquake and, particularly, with its intensities on Oahu. Although estimates of the epicentral location and magnitude of the earthquake are presented in the report, these are based on its intensity distribution. No attempt was made in the study to obtain and analyze copies of the seismographic records of the earthquake.

The extension of the study to include the possible Diamond Head fault, whose existence was first suggested by Furumoto et al. (1980) resulted from notice that the epicenter of the 1948 earthquake, as estimated in the study, was on the trend of the fault.

Sources of information on the earthquake

The principal sources of information as to the effects of the 1948 earthquake on whose basis its intensities may be estimated are the two contemporary Honolulu newspapers, the Honolulu Advertiser and the Honolulu Star-Bulletin. For brevity, the abbreviations Advertiser or Adv, and Star-Bulletin or SB, respectively, and the day and month of issue without the year, are used at places in the following text and in tables in citing these sources.

Coverage given in the Honolulu newspapers to the Hawaiian earthquakes of late June 1948 was at least equalled by their coverage of a major earthquake that had occurred in Japan a few days earlier than the principal Hawaiian quake, and of the aftershocks of the Japanese earthquake.

There were at the time of the June 1948 earthquake two seismological observatories in Hawaii: the Honolulu Magnetic Observatory (HMO) of the U. S. Coast and Geodetic Survey (CGS) at Barbers Point, Oahu; and the Hawaiian Volcano Observatory (HVO) at Kilauea Volcano, Hawaii. Information on the quake emanating from these observatories appeared in a seismological note published in the Bulletin of the Seismological Society of America (BSSA) (Anon, 1948), in the Volcano Letter published by the HVO (Finch, 1948), and in the issue of United States Earthquakes for 1948 published by the CGS (Murphy and Ulrich, 1951).

The occurrence of the earthquake has been noted in a list of earthquakes of interest on Oahu compiled by G. A. Macdonald (1960?), in a history of Hawaiian earthquakes (Furumoto et al., 1973) and in comments on that history (Macdonald, 1973), in a further review by Furumoto et al. (1980), and in the Earthquake History of the United States (Coffman et al., 1982).

Earthquake intensities

The Modified Mercalli (MM) scale of earthquake intensities (Table 1) is used in this report. The intensity estimates are presented in two forms:

i) Integer values in the 12-valued, discrete-step original version of the MM scale of 1931 (Wood and Newmann, 1931) or the version of 1956 (Richter, 1958), indicated, as conventionally, by roman numerals; and

ii) Values in a continuous-scale equivalent, indicated by arabic numerals with decimals (Cox, 1985b).

At the outer boundary of conventionally mapped "iso-intensity" zones:

$$I' = I - 0.5$$

where I = conventional (integer-valued) intensity
I' = intensity in continuous-scale equivalent

Places

The locations of places on Oahu where the 1948 earthquake was reported felt are shown in the location maps for the island and for Honolulu (Figures 1 and 2).

Table 1. Modified Mercalli Scale of 1931, 1956 abridged version*

I. Not felt. Marginal and long-period effects of large earthquakes.

II. Felt by persons at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frame creak.

V. Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D* cracked. Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle—CFR).

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments—CFR). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations—CFR). Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Masonry types:

A. Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

B. Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

C. Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

D. Weak materials, such as adobe; poor mortar; low standards of workmanship, weak horizontally.

*Richter (1958) (CFR in annotations)

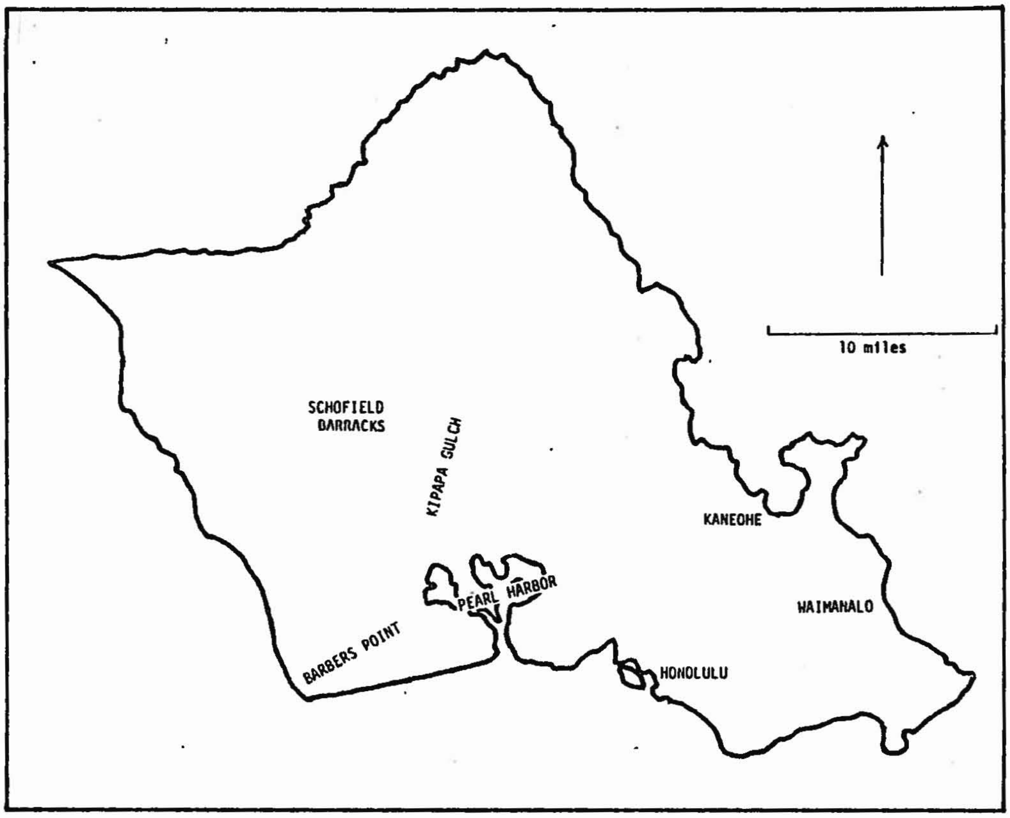

Figure 1. Location map, places on Oahu.

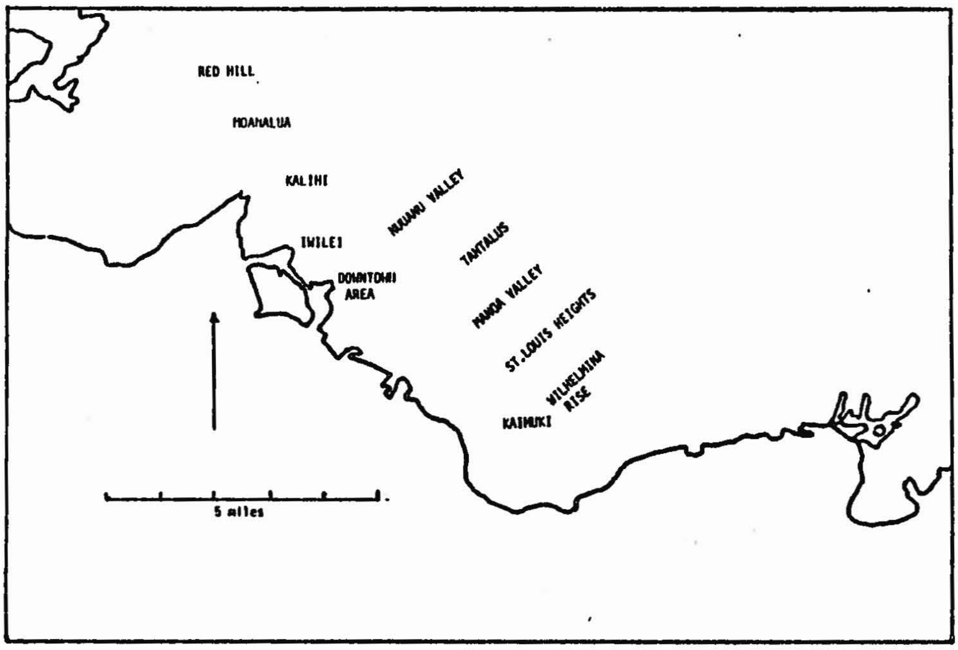

Figure 2. Location map, places in Honolulu.

BACKGROUND INFORMATION ON THE 1948 EARTHQUAKE AND ITS ASSOCIATED SHOCKS

Number, dates, and times of shocks

Shocks of 26-28 June

The reported dates and times of Hawaiian earthquakes occurring from the 26th through the 28th of June, 1948, are listed in Table 2, together with notes on their reported sources, character, and effects.

Although the occurrence of a quake on 26 June was reported in three sources, the third (Macdonald, 1960?), cited the first and second, and the report in the second (U. S. Earthquakes, Murphy and Ulrich, 1951) was probably derived from the first, the Volcano Letter (Finch, 1948). It should be noted that the time of the quake of 28 June attributed to Finch by both the Star-Bulletin and the Advertiser is exactly the same (if that reported in the Advertiser is corrected from pm. to am. and rounded to the nearest minute) as that reported by Finch in the Volcano Letter. It should also be noted that there is no entry in the Volcano Letter record that corresponds to the time of the main quake of 28 June. It seems inescapable that the reports of a quake on 26 June result from the erroneous substitution of 26 for 28 in the Volcano Letter.

The time of 01:41:11 reported in the Advertiser for the quake of 28 June probably represents the time of the beginning of the main shock as recorded at HMO. This time and that reported for the observation of the earthquake on Molokai (SB) are probably closer to the origin time of the earthquake than the time it was recorded at HVO. The time of 01:38, although identified in U. S. Earthquakes as that of the main shock, is described in the seismological note in the BSSA as that of the beginning of a series of shocks. The reports may be reconciled if it is assumed that the main shock, originating at 01:41, was preceded by a foreshock originating at 01.38.

There is no information either confirming or refuting the report in the Star-Bulletin that an aftershock was felt in Honolulu 10 minutes after the main shock (ie. at 01:51) unless, possibly, the very feeble quake reported as recorded at HVO at 10:51 actually occurred at 01:51. No quakes other than the principal shock and the aftershock of 01:51 were reported felt anywhere on 28 June, and the aftershock was not reported felt on any island other than Oahu.

Possible foreshock on 17 January

What may have been a foreshock of the 28 June earthquake was a disturbance occurring 6 months earlier, on 17 January 1948 at about 19:32. According to the Advertiser (18 Jan), which described it as "what was believed to be a light earthquake [that] shook portions of Honolulu", it was recorded on a Weather Bureau barograph. However, the seismograms of the HMO (at Barbers Point) had not been read when the newspaper went to press; neither newspaper mentioned the quake later; the quake was not reported in U. S. Earthquakes; and the only quake reported for 17 January in the Volcano Letter was a feeble one at 09:50 centered near the Hilina Pali on Hawaii.

If the disturbance was a natural earthquake, it presumably originated near Honolulu. The reason for associating it with the June earthquake will become apparent.

Estimated epicentral location and Oahu intensity of principal shock

The dismantling of the HMO seismographs at Barbers Point (Adv, 29 Jun), apparently very soon after the beginning of the main shock, undoubtedly contributed to uncertainty whether the earthquake's epicenter was located closer to Molokai or to Oahu.

Table 2. Dates, times, origins, and characteristics reported for Hawaiian earthquakes, 26-28 June 1948

Day	Time, HST	Origin	Character and effects	Notes	References
26	01:42	Under Oahu	Slight at HVO		6, 7, 8
28	---	---	Effects in Honolulu		9
28	01:38	Molokai vicinity	Beginning of series of quakes		5
28	01:38	---	Major effects on Oahu		7
28	01:38	Oahu			10
28	01:41:11	---	(Recorded at HMO?)		2
28	01:42	Molokai vicinity	Recorded at HVO	a	3
28	01:51	---	Felt in Honolulu	b	6
28	10:51	---	Very feeble at HVO		4
28	13:42:24	Off Oahu	Recorded at HVO	c	3
28	01:41	---	Felt on Molokai		

Notes: a. Origin 125 to 250 miles from HVO
b. Time about 10 min. after main shock
c. Origin 150 miles from HVO, probably under water

References:
1. Star-Bulletin (28 Jun), apparently from HMO
2. Star-Bulletin (28 Jun), attributed to R. H. Finch, HVO
3. Star Bulletin (28 Jun)
4. Advertiser (29 Jun), attributed to R. H. Finch, HVO
5. Seismological note (Anon., 1948)
6. Volcano Letter (Finch, 1948)
7. U. S. Earthquakes (Murphy and Ulrich, 1950)
8. Macdonald (1960?) notes, citing refs. 5 and 7
9. Furumoto et al. (1973), citing ref. 7
10. Earthquake History of U. S. (Coffman et al., 1982, citing ref. 7

The BSSA (Anon, 1948) reported that the shock was "apparently centered near the island of Molokai, but no major damage was reported there". Furumoto et al. (1973) considered, from the HVO reports, that the epicenter was probably in the Kalohi Channel between Molokai and Lanai, where they plotted the symbol for a quake with a Richter magnitude between 4.0 and 4.9 that probably represented the 1948 earthquake. However, recognizing that the effects of the quake were far less severe on Molokai than on Oahu, Furumoto et al. (1980) considered that the epicenter was on or very near Oahu, and they referred to it as an Oahu earthquake.

The latter authors (Furumoto et al., 1980) estimated the Oahu intensity of the principal shock as MM VI.

EFFECTS OF THE 1948 EARTHQUAKE AND ASSOCIATED SHOCKS

Possible January foreshock

Regarding the possible foreshock that occurred on 17 January at about 19:32, the Advertiser reported:

> Hundreds of phone calls to police and the Advertiser were made by startled residents, some of whom feared the tremors might have been the results of an explosion...
>
> The shock was particularly evident in the upper elevations of the city. Residents of upper Manoa, St. Louis Heights and Wilhelmina Rise reported furniture shaken and windows rattled.

Principal shock

In Honolulu

The most important effects of the main shock were those in Honolulu.

According to the Star-Bulletin (28 Jun), most residents on Oahu were awakened by the shock and "many of them scurried into the streets". According to the Advertiser (29 Jun), the "peaceful slumber of thousands of Honolulans...was rudely disturbed... They fled from their apartments and homes...in their nightclothes". However, the Star-Bulletin (29 Jun) added: "A few persons admitted, with some embarrassment, that they had slept right through the earthquake".

The earthquake caused no serious injuries to people, although one man in the bathroom of a Kalihi home, frightened by the earthquake, fainted and had to be treated (SB, 28 Jun). The lack of injuries was so notable that the Star-Bulletin (29 Jun) reported the death of a goldfish in an aquarium

Plaster cracks were reported in at least 20 Honolulu buildings (Adv, 29 Jun). Damages reported to specific downtown buildings and their contents are listed in Table 3. The "other damages indicated in the table were as follows:

Davies building: Four large plate-glass windows broken (Adv, 29 Jun);
Alexander & Baldwin building: Some fluorescent lamps displaced from their sockets (SB, 28 Jun);
McInerny building: One window cracked (Adv, 29 Jun);
Judiciary building: Books in law library thrown from shelves to the floor;
Aloha tower: Large clock stopped (SB, 28 Jun).

The largest loss reported, $40,000, was that at Tripler Hospital, then nearing completion (SB, 29 Jun). Although there were some windows cracked, most of the damage there was in the form of plaster cracks around doors or windows or at building joints designed to permit differential motion during earthquakes (Adv, 29 Jun; SB 29 Jun). There was evidence of nearly 2 inches of motion on some of these joints (SB, 29 Jun).

The only other loss reported in economic terms was $10,000 damage at the American Can Co. office and warehouse in Iwilei. This damage included cracks in the reinforced concrete walls around the elevator shaft and stairway in the office building and in the concrete-slab roof of the warehouse, and broken windows caused by springing of their steel sashes (SB, 29 Jun).

Table 3. Damage from 1984 earthquake to specific downtown Honolulu buildings and their contents.

Building	Location (a)		Damage (b)	References (c)
Young	Bishop, Hotel to King	SE	C	Adv
Bishop Bank	Bishop, King to Merchant	SE	C	SB, Adv
Theo. H. Davies	Bishop, Merchant to Queen	SE	C,O	SB, Adv
Dillingham Transport	Bishop, Queen to Halekauwila	SE	C	SB, Adv
Bishop Trust	Bishop & King,	W	C	SB, Adv
Castle & Cooke	Bishop & Merchant,	N	C	SB, Adv
Alexander & Baldwin	Bishop, Merchant to Queen	NW	C,O	Adv
Star-Bulletin	Merchant, betw. Bishop & Fort	SW	C	Adv
McInerny	Fort & King,	S	C,O	???
Cunha			C	SB, Adv
Hocking			C	SB, Adv
Waite			C	SB, Adv
Aloha Tower	Foot of Fort		O	
Iolani Palace	Hotel to King, Likelike to Richards		C	Adv
Judiciary	King and Mililani	S	C	???
Territorial Office	King & Punchbowl	W	O	Adv

Notes: (a) Locations:
Streets and sides or street intersections and corners
(b) Damages:
C = Cracks in ceilings or walls, probably limited generally to gypsum or cement plaster except as indicated in text.
O = Other damages, see text.
(c) References:
SB = Star-Bulletin, 28 Jun
Adv = Advertiser, 29 Jun

At the Bishop Museum in Kalihi, stacks in the library were overturned and books were thrown from shelves to the floor elsewhere, artifacts and specimens in collections and exhibits were thrown down, glass (of display cases ?) was broken, a rare Solomon Islands bowl and a rare Hawaiian image were shattered, and a 3-1/2 foot statute was moved 6 inches in its case (SB, 28 Jun; Adv, 29 Jun).

According to the Advertiser (29 Jun):

> Most concentrated damage to any residential area was reported by residents of Tantalus. Heavy water tanks were moved from their foundations causing heavy leakage. A fireplace chimney was cracked, a grand piano was moved across a room, and much heavy furniture jarred from the walls.
>
> Canned goods, medicines, dishes, chandeliers, pictures, mirrors, and lamps were broken. Plumbing was jarred from its connections in some of the older houses and windows dropped out of their frames.
>
> Half-ton boulders blocked one private driveway. ...

No major damage was reported by Oahu's military installations. However, large cracks were evident in the center stairwell of all four floors of the "Pineapple Pentagon" at Fort Shafter, and several trophy and display cases were knocked off hangars on the walls there. A 70-foot crack marred one wall of a new barracks at Fort Shafter.

According to the Star-Bulletin (Jun 28), some joists were sprung in the headquarters building at Fort Shafter.

No damage was reported at the airport, but a traffic controller in the control tower was thrown from his chair (SB, 28 Jun).

In Kaimuki, several sidewalks were reported badly cracked (Adv, 29 Jun).

According to the contemporary reports, one water pipe was broken. The Star-Bulletin identified this as a "3-inch pipe serving about 12 families in the Makiki homestead district" (Papakolea ?). Macdonald (1973), apparently familiar only with the brief notice in the BSSA (Anon, 1948) that did not locate the break, attributed it to a pipe in a World War II housing area north of St. Francis Convent in Manoa Valley. There may, therefore, have been two water-pipe breaks.

A telephone pole at Kapiolani Blvd. and Curtis St., already weakened by termites, broke, but was held up by the wires. There was a one-hour power outage in Nuuanu (SB, 28 Jun). Fears of gas-main breaks proved false, and the only effect of the quake on telephone service was heavy usage immediately after the quake (SB, 28 Jun; Adv, 29 Jun).

Elsewhere on Oahu

Broken windows, cracked foundations, loosened boulders, and water and telephone service interruptions at scattered locations on the island were reported to the police (Adv., 29 Jun).

A landslide blocked Kamehameha Highway in Kipapa Gulch, but the highway was cleared within about three hours (SB, 28 Jun; Adv, 29 Jun). There was another landslide on Moanalua Road at Red Hill (Adv, 29 Jun).

A short of the power main serving the Koolaupoko substation on the windward side of the island resulted in a blue flash seen in Honolulu (Adv, 29 Jun) and caused a 2-hour power outage from Kaneohe to Waimanalo (SB, 28 Jun).

On other islands

On Molokai, the main shock was reported as a "sharp temblor ... felt at 1:41 a.m. (SB, 28 Jun), residents of Kaunakakai describing it as "not as bad nor as long" as a quake that had occurred in 1940.

There were no reports in the newspapers of observation of the earthquake on Lanai or Maui; and, by first reports, it was not felt on Hawaii (Adv, 29 Jun). However, it was later reported, without detail, to have been felt in Hilo (Finch, 1948).

Aftershock

The aftershock of 01:51 on 28 June was reported as "a very slight jar which rattled windows and lasted perhaps a second" in Honolulu, which was the only place where its observation was mentioned (SB, 28 Jan).

ESTIMATED INTENSITIES OF THE 1948 EARTHQUAKE AND ASSOCIATED SHOCKS

January foreshock

The rattling of windows caused by the January foreshock is an effect characteristic of earthquakes with MM intensities of IV. Because this effect seems to have been noted principally if not entirely "in the upper elevations of the city", the average intensity of the quake in Honolulu was probably near the boundary between intensities III and IV.

Principal shock

In Honolulu

The awakening of many, and perhaps most, of the residents of Honolulu by the principal shock suggests an intensity of MM V, as would the running outdoors of a few of them, and some breakage of dishes and some cracking of windows. The reports that most of those awakened ran outdoors, if they could be trusted, would suggest an intensity of VI. The considerable breakage of dishes and glass, the movement of heavy furniture, and the cracking of a chimney on Tantalus are strongly suggestive of an intensity of VII, as is the extensive fall of books, artifacts, and specimens at the Bishop Museum, and perhaps the fall of books at the Supreme Court library, and the toppling of the air traffic controller at the airport from his chair.

Most of the reported cracking of ceilings and walls, including that at Tripler Hospital, could be accounted for by an intensity of VI, but the 70-foot crack in the wall of the new barracks at Fort Shafter, and particularly the cracking of the reinforced-concrete walls and roof slab of the American Can Co. in Iwilei strongly suggest local intensities of at least VII.

It appears that the intensities of the earthquake on Tantalus, which is a cone of essentially unconsolidated volcanic cinders, and in the Iwilei district, where there the shallow subsurface sediments are weak, were higher than the intensities experienced generally. Considering overall the reported effects of the quake in Honolulu, it appears that the intensity of VI estimated for it by Furumoto et al. (1980) cannot be improved on as an average for the city, but that its intensity on Tantalus and Iwilei, and possibly in Kalihi and at Fort Shafter, was VII.

Elsewhere on Oahu

Specific intensities of the earthquake at places on Oahu other than Honolulu cannot be estimated because the effects of the earthquake reported elsewhere, other than the power-main short, are not referred to specific places. It appears, however, that its intensity elsewhere on the island was generally V or less.

On other islands

The report that the June 1948 earthquake was "not as hard" at Kaunakakai, Molokai, as one that had occurred in 1940 provides little guidance to the estimation of the Molokai intensity of either quake. A magnitude 6 earthquake had occurred on 17 June 1940, but its epicenter was northeast of the northeast coast of Hawaii, and its intensity on Molokai is unlikely to have exceeded MM II; and an earthquake of lesser intensity would not have been noticed, even during the daytime. The report may perhaps have referred to the January 1938 Maui earthquake, for which Holman (1982) has estimated an intensity in the Kaunakakai vicinity on the border between VI and VII. The lack of reports of significant effects of the 1948 earthquake on Molokai suggests strongly that its intensity on that island was much less than VI, and perhaps only about IV.

Even if the 1948 earthquake was felt at Hilo, as reported by Finch (1948), the lack of other reports of its observation on Hawaii suggest that its intensity there was no greater than II or perhaps III.

There is no available information from which to estimate the intensity of the quake on Maui or Lanai.

The report that it was felt at several places on Kauai suggests, considering the time of its occurrence, an intensity of III or IV on that island.

<u>Aftershock</u>

The effects reported for the aftershock occurring about 10 minutes after the principal shock suggest that, if the aftershock actually occurred, it had an intensity of II in Honolulu.

<u>Summary</u>

The estimated intensities of the earthquake are summarized in table 4 in the form of averages and ranges of uncertainty for various places expressed as values in the continuous-scale equivalent of the MM scale.

Table 4. Estimated average MM intensities (I') of the 1948 earthquake and its foreshock and aftershock

Place	Intensity		
	Foreshock 17 January 19:32	Main shock 28 June 01:41	Aftershock 28 June 10:51
Tantalus and Iwilei		2.2+/-0.7	
Honolulu generally	3.5+/-1.0	6.0+/-0.7	2.0+/-2.0
Western Oahu		5.5+/-1.0	
Molokai		4.0+/-1.5	
Hilo, Hawaii		2.0+/-1.5	
Kauai		3.5+/-1.2	

INTENSITY DISTRIBUTION AND SOURCE OF THE 1948 EARTHQUAKE

As noted by Furumoto *et al.* (1980), an epicenter located "off Oahu" or "under Oahu" would account better for the relative intensities of the main shock of 28 June on Oahu and Molokai than than the suggested alternative, about 150 miles (or 125 to 250 miles) from the HVO and in the vicinity of Molokai.

A relationship between intensity and the combination of magnitude and hypocentral distance based by Cox (1985) on the results of a study by Howell and Schultz (1975) may be used, together with the geographic distribution of intensities of the earthquake estimated from its effects at various places, to estimate both the hypocentral location of the earthquake and its magnitude. The relationship is:

$$\ln(I'+0.5) = \ln(M-1) + 0.877 - 0.144 \ln r - 0.00057\, r$$

where I' = MM intensity in the continuous scale
M = Richter magnitude
$r = (x^2 + h^2)^{1/2}$ = hypocentral distance, km
x = epicentral distance, km
h = focal depth, km

Intensity distributions calculated on the basis of this relationship assuming various possible magnitudes and focal depths for the 1948 earthquake were superimposed on a map showing the intensities estimated from the effects of the earthquake. The calculated distribution best fitting the estimated intensities, shown in figure 3, is based on a Richter magnitude of 4.8 and an epicenter at 21.2° N, 157.9° W, just offshore from Honolulu, and a focal depth of 5 km.

Neither the estimated magnitude nor the estimated hypocentral location of the 1948 earthquake should be assumed precise. However, a quake with a significantly greater magnitude should have had intensities on Kauai, Molokai, and Hawaii considerably greater than those estimated from the effects of the 1948 earthquake and should expectably have been reported felt on Maui and Lanai. A quake with a significantly smaller magnitude or significantly greater focal depth should have had an average intensity at Honolulu considerably less than that estimated from the effects. It seems fairly certain that the 1948 earthquake had a magnitude within 0.5 units of that indicated above, a focal depth of less than 20 km, and an epicenter within about 50 km of that indicated above.

Because the intensity of the earthquake was clearly higher on Oahu than on any other island, and because the epicenter of the earthquake seems to have been very close to Oahu, the earthquake may be referred to appropriately as the Oahu earthquake of June 1948.

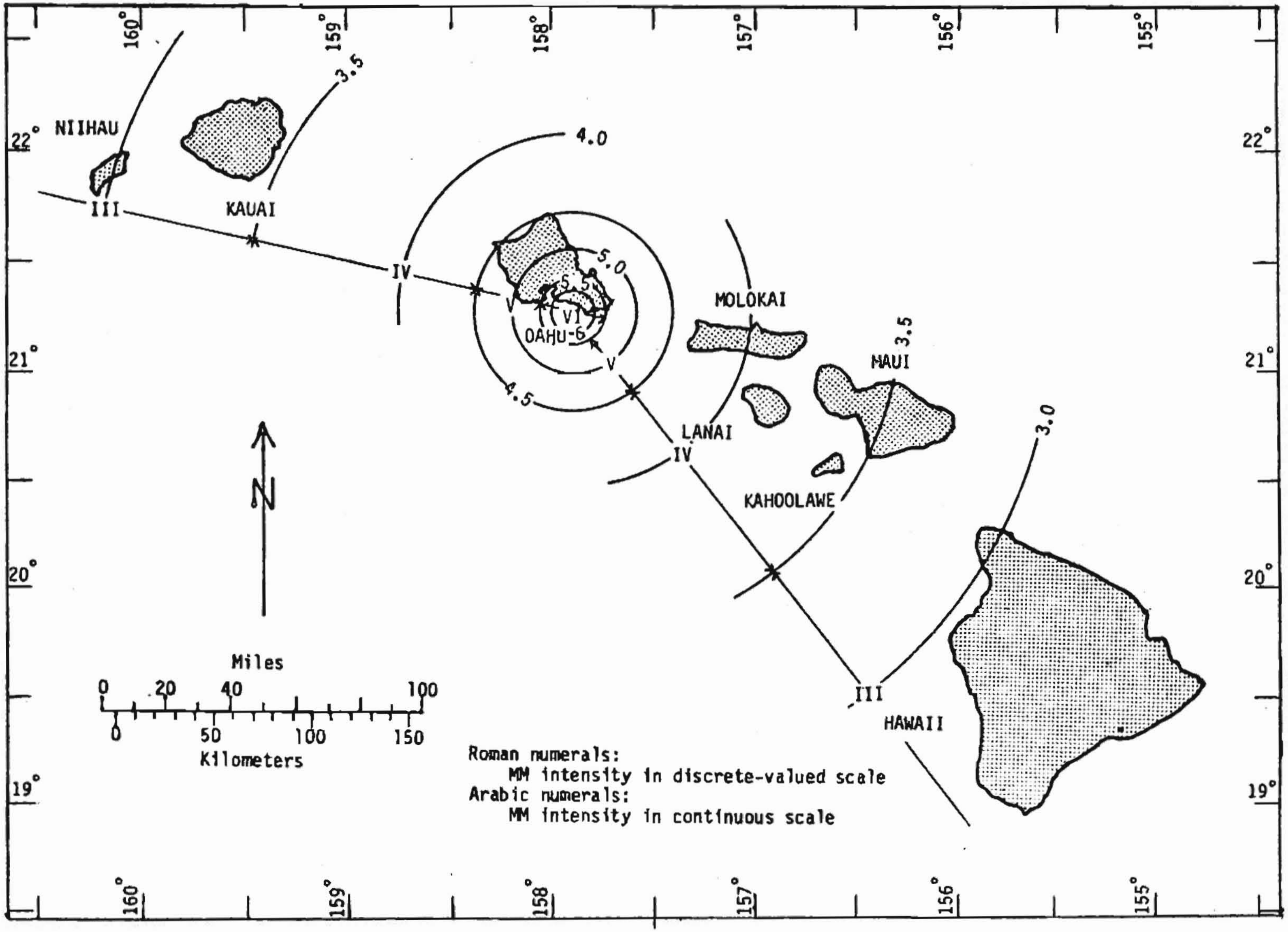

Figure 3. Calculated intensity distribution, Oahu earthquake of 1948.

THE HYPOTHETICAL DIAMOND HEAD FAULT

Introduction

The epicenter of the June 1948 earthquake, as estimated above, falls on the trend of what has been called the Diamond Head fault, a possible fault passing through or close to Diamond Head and Koko Head and extending to the east-northeast (figure 4). For brevity in what follows, the abbreviation DHf will be used generally in referring to this possible fault.

The existence of the DHf was suggested originally by Furumoto et al. (1980) on the basis of the approximate alignment of the epicenters of seven earthquakes occurring in the period from 1962 through 1977, as indicated in a plot by Estill (1979). Furumoto et al. (1983) recognized that two additional earthquakes occurring in 1981 quakes had epicenters falling approximately on the same line.

Earthquakes originating or possibly originating along the fault

The historic earthquakes that are known to have originated along the DHf, and others that were felt on Oahu and might have originated along the fault, are listed in Table 5. For the nine earthquakes associated with the fault by Furumoto et al. (1980 and 1983) (those listed in the table with identification numbers), the epicentral locations, focal depths, and magnitudes shown were derived from those sources. The equivalent data for the 1948 earthquakes are those derived in this study. The epicentral location of the August 1956 quake, whose epicenter was about 15 km. south of the northeasterly extension of the DHf, and the epicentral location and magnitude of the March 1979 earthquake, whose epicenter was on the trend of the DHf about 200 km west-southwest of Honolulu, were drawn from the general study of the intensities of historic earthquakes felt on Oahu during the period from 1859 through 1983 (Cox, in press), as were the verbally described epicentral locations.

Earthquake magnitudes other than those derived from the sources indicated above were estimated from the Honolulu intensities of the earthquakes using the same formula used in estimating the magnitude and epicentral location of the principal 1948 earthquake. In the case of the 15 quakes of uncertain origin, the epicenters were assumed to be no more than 175 km. from Honolulu, at the east-northeast limit shown for the fault in figure 3; and maximum possible magnitudes were estimated on that basis.

As will be shown (Cox, in press a), the record of earthquakes felt on Oahu since 1859 may be considered complete with respect to those of I' => 4.5 in Honolulu, and the record since 1910 may be considered complete with respect to the quakes of I' => 3.5 in Honolulu. Hence it may be assumed that, although table 4 may well include some quakes that did not originate along the DHf, it includes all quakes originating along the fault since 1859 whose magnitudes were 5.3 or greater and all since 1910 whose magnitudes were 3.6 or greater.

Critique of evidences for the existence of the fault

Seismological evidence

The approximate alignment of nine epicenters along the trend of the possible fault has little significance in itself. Of much greater significance is the concentration ratio $r = d_z/d_a$, where d_z is the concentration of epicenters falling within the possible fault zone and d_a is the average concentration of epicenters in the vicinity.

To provide for consistency in the data used in the calculation of r values, use was made of Estill's (1979) plot of 1961-1977 epicenters in the area from Oahu to the northern part of Hawaii (figure 5). In estimating d_z for the DHf, the fault zone was considered 150 km long and 20 km wide. The value of d_a for the

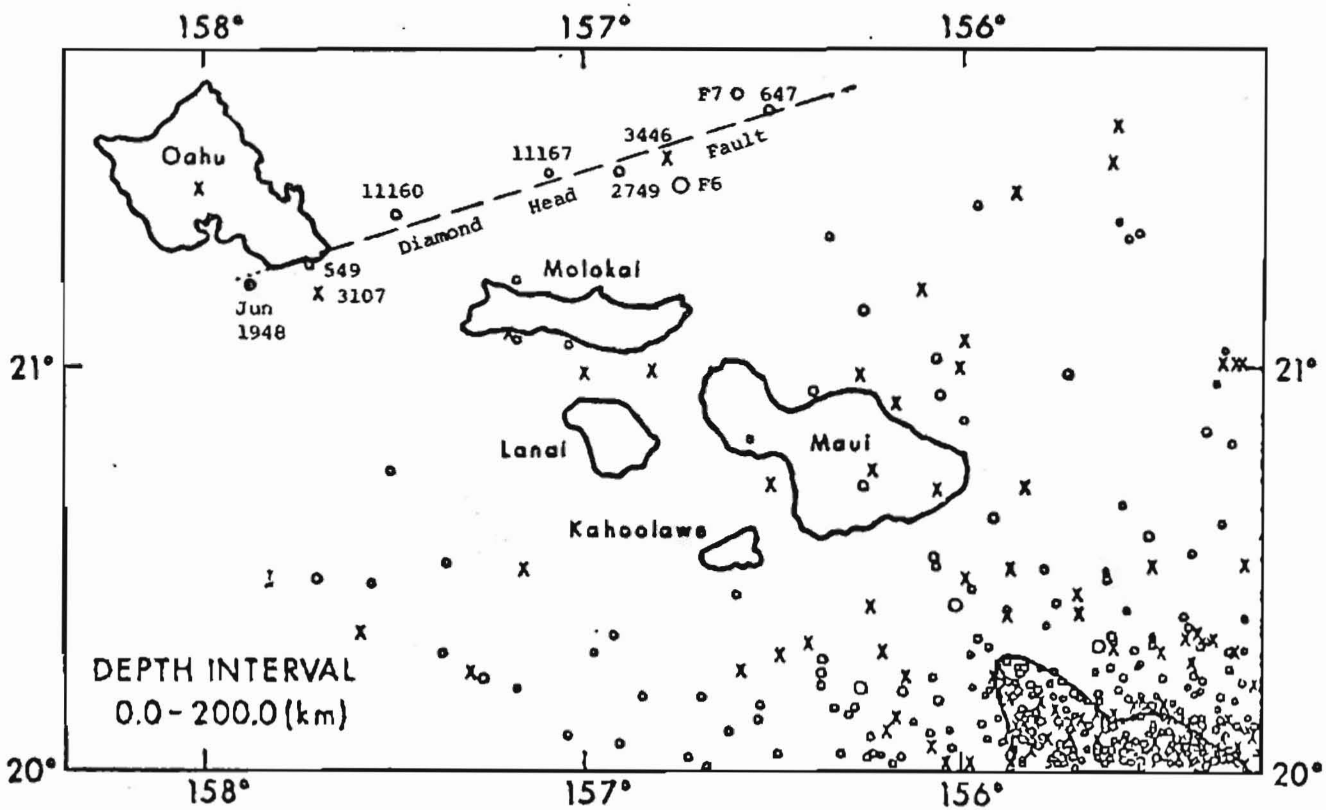

Figure 4. The hypothetical Diamond Head fault and epicenters of earthquakes suggesting its existence.

Table 5. Earthquakes originating or possibly originating along the hypothetical Diamond Head fault.

No. a)	Date and time (GMT)	Lat. b)	Long. b)	h, km b)	M b)	I' c)	x, km d)	Est.M e)
		Hypocenter						
	1869 Jan 19 04:01	NE Oahu vic.				2.8	=<175	=<4.0
	1895 Dec 9 09:35	Oahu vic.				5.0	=<125	=<6.3
	1895 Dec 9 13:37	Oahu vic.				1.5	=<175	=<2.9
	1919 Jan 29 03:23	W Molokai vic.				2.5	=<175	=<3.9
	1923 Dec 26 05:16	Oahu-Lanai-Molokai vic.				4.0	=<175	=<5.3
	1925 Jul 30 07:49	Oahu vic.				2.5	=<175	=<3.9
	1934 Sep 6 05:05	Oahu vic.				3.5	=<175	=<4.8
	1936 May 12 04:15	Oahu vic.				1.3	=<175	=<2.7
	1936 Aug 16 18:08	Oahu vic.				1.8	=<175	=<3.2
	1939 May 14 02:02	Oahu vic.				1.3	=<175	=<2.7
	1948 Jan 18 05:32	21.2?	157.9?			3.5	15	3.6
	1948 Jun 28 11:41	21.2	157.9	(5)	(4.8)	6.0	15	
	1948 Jun 28 11:51	21.2?	157.9?			2.0	15	2.6
	1951 Dec 12 23:18	Diamond Hd.-Koko Hd.				2.0	10	2.6
	1951 Dec 12 23:21	Diamond Hd.-Koko Hd.				2.0	10	2.6
	1952 Dec 8 ?	Oahu vic.				1.8	=<175	=<3.2
	1955 Nov 23 06:43	NE Oahu vic.				1.5	=< 50	=<2.5
	1956 Feb 19 03:04	SE Oahu vic.				1.8	=< 50	=<2.7
	1956 Aug 7 17:05	21.2	157.4	24		3.0		3.7
549	1962 Mar 18 00:33	21.27	157.72	39	3.7			
647	1962 Jun 11 08:11	21.63	156.50	16	3.4			
2749	1968 Mar 31 10:56	21.50	156.90	13	4.0			
3107	1969 May 28 02:38	21.20	157.70	33	?			
3446	1969 Oct 7 14:20	21.32	157.10	5	3.1			
	1976 Jan 15 20:00	SE Oahu vic.				2.8	=< 50	=<3.1
	1976 Jan 22 ?	SE Oahu vic.				3.8	=< 50	=<4.2
11160	1977 Sep 5 19:40	21.38	157.50	5	4.1			
11167	1977 Oct 10 09:25	21.50	157.10	5	3.1			
	1979 Mar 29 09:07	20.6	158.8		5.5	4.0		
F6	1981 Mar 5 14:10	21.42	156.77	10	5.0	5.0		
F7	1981 Mar 6 02:44	21.67	156.62	10	4.0	2.0		

Notes:
- a) Identification numbers in Furumoto et al. (1980) and Furumoto et al. (1983).
- b) Epicentral locations indicated by geodetic coordinates, focal depths (h), and Richter magnitudes (M) are as listed by Furumoto et al. (1983) except in the case of the 1948 quakes for which the data are from this study.
- c) Honolulu intensities (I') as estimated in this study or in Cox (in press).
- d) Estimated epicentral distances from Honolulu.
- e) Magnitudes estimated from Honolulu intensities and epicentral distances.

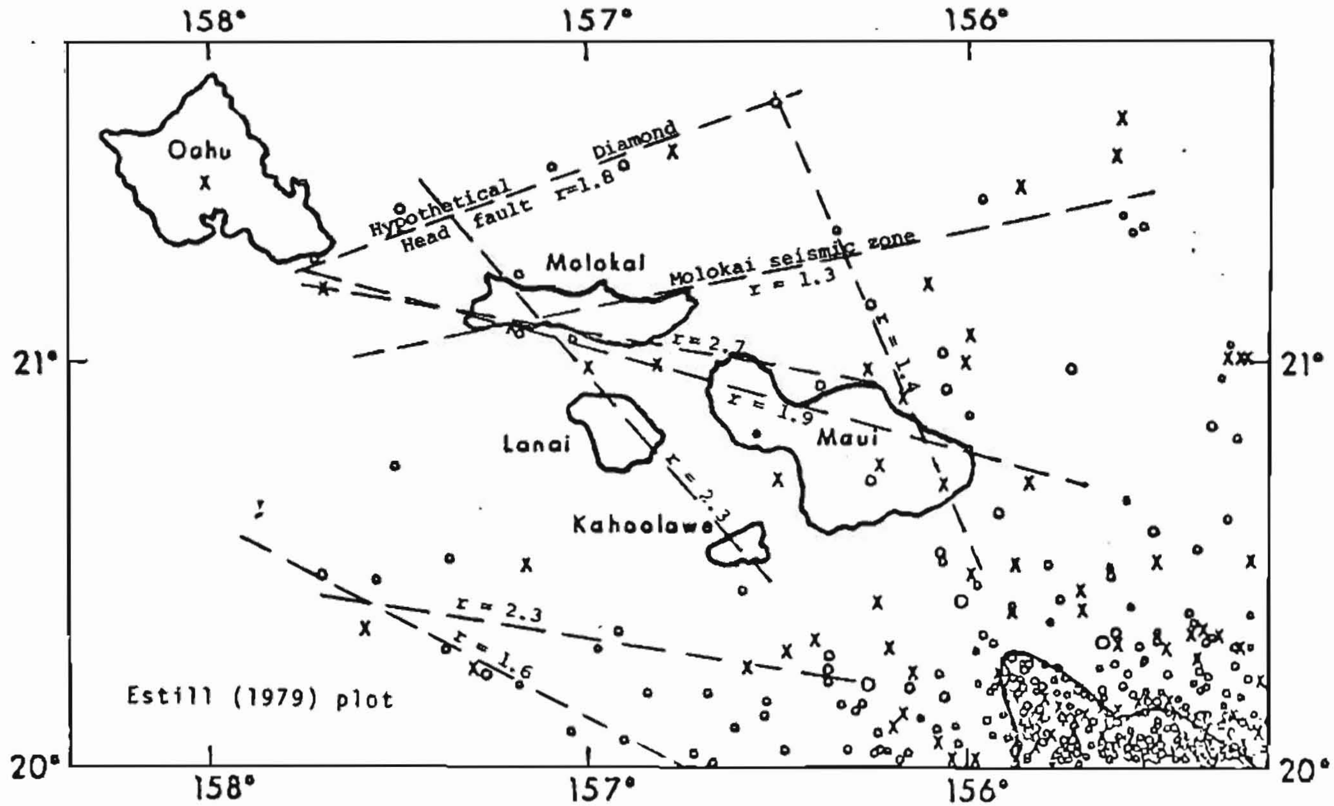

Figure 5. Epicentral distribution ratios for conceivable fault zones in the Oahu - Molokai - Lanai area.

vicinity was the concentration within a circle having the same center as the zone and twice its area. The concentration ratio for the DHf calculated from these values, r = 1.8 is significantly greater than one. However, Estill's plot suggests that there were other zones in which there are epicentral concentration ratios that are as high or higher. To Figure 5 have been added lines representing:

a) the axes of three zones whose dimensions were assumed identical to those described above for the DHf, each of which contained one or two of the epicenters in the DHf zone, for which concentration ratios between 1.4 and 2.7 were calculated;

b) the axes of two zones with identical dimensions southwest of Lanai, for which concentration ratios of 1.6 and 2.3 were calculated; and

c) the axes of two additional zones for which the dimensions and the radii of the areas in the vicinity were considered 50 percent larger. For one of these, designated by Furumoto et al. (1980) as the Molokai fault zone, the calculated ratio is 1.3. For the other, a zone including most of Maui and Molokai and a part of Lanai, the calculated ratio is 1.9.

The preferential orientation of epicenters in the DHf zone has thus been found no greater than the preferential orientation of epicenters in other linear zones with comparable dimensions in the region.

In considering the implications of the preferential orientation of epicenters in any such zones, it is recognized that there may easily be 20-km errors in the determination of the epicenters. Among various epicentral locations reported for the earthquake of 5 September 1977, for example, there are ranges of 0.3° in both latitude and longitude. Errors in epicentral location should, however, be expected to result in reduction rather than enhancement of apparent epicentral concentration ratios.

Other geophysical, geological, and bathymetric evidence

In the context of their discussion of the DHf, Furumoto et al. (1980) introduced a map showing magnetic anomaly traces, volcanic rift zones, and a few faults or suspected faults based on another compilation by Estill (1979). Except for the correction of an error in the designation of one of the parallels of latitude, this map is reproduced in figure 6.

The fault shown southwest of Lanai in figure 6 corresponds to the zone zone shown in figure 5 for which r = 1.6; and the zone identified in figure 5 as the Molokai seismic zone represents a westward extension of the Molokai fracture zone shown in figure 6. Otherwise there is no correspondence between the lineaments shown in Figures 5 and 6; and there is in figure 6 no indication of the existence of the DHf.

The major rift zones of the Koolau and Waianae volcanoes of Oahu are not shown in figure 6, but these rift zones are oriented northwest-southeast. Both Diamond Head and Koko Head lie on subsidiary, geologically late, rift zones of the Koolau volcano, but these rifts strike north-northeast, not east-northeast, and hence intersect the DHf.

If there had been recent activity on the part of the DHf between Diamond Head and Koko Head, as suggested by the estimated epicentral locations of the 1951 earthquakes, or in the vicinity of these cones as suggested by their bracketing between the epicenters of the 1961-1981 quakes and the estimated epicenters of the 1948 quakes, or even if there had been activity on this part of the fault since the formation of Diamond Head and Koko Head, evidences of the activity should be seen in the form of discocations of the tuff beds of the cones along lines approximately parallel to the general trend of the DHf. There are no such evidences either in the cones themselves or in parts of Oahu to the north of them. The lack of such evidence does not prove, of course, that the DHf does not exist and has not been recently active if it does not actually cross a land area.

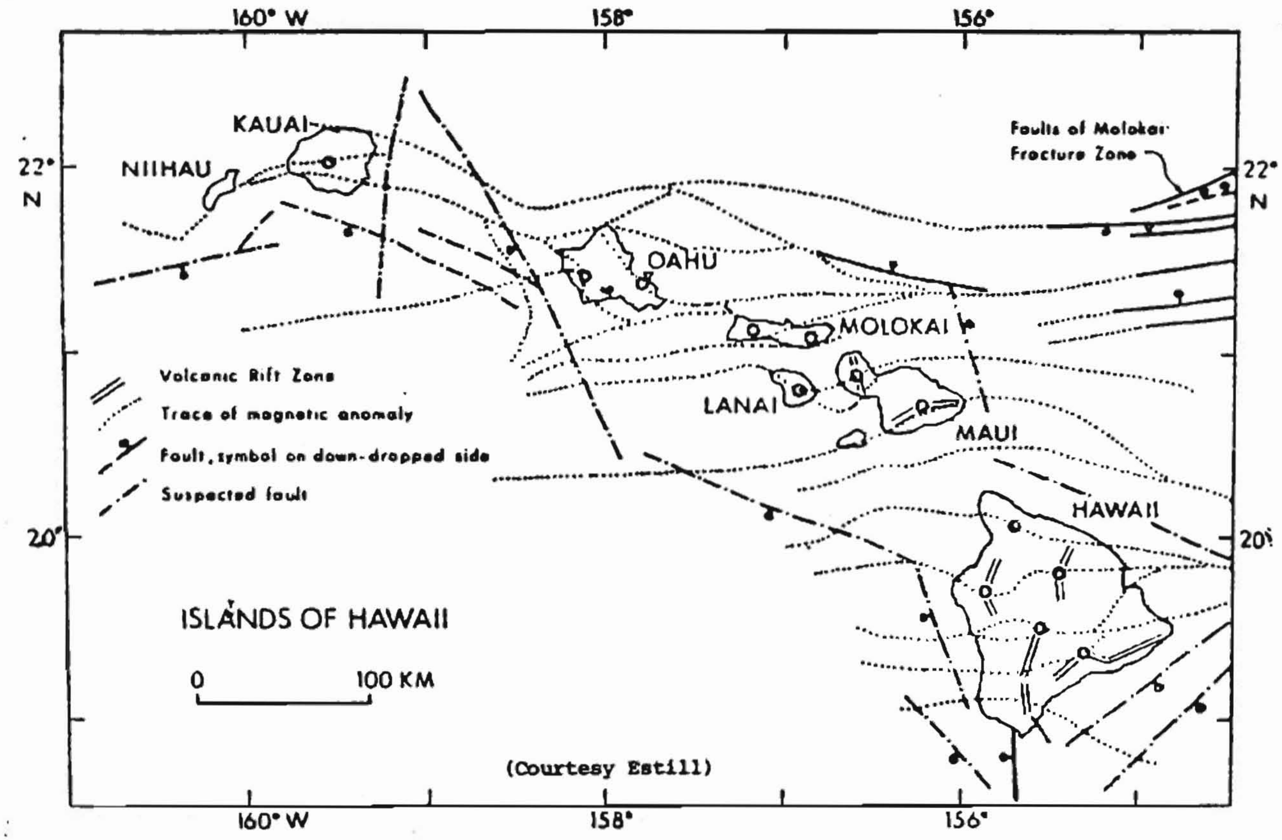

Figure 6. Geological and geophysical lineaments in the Hawaiian area.

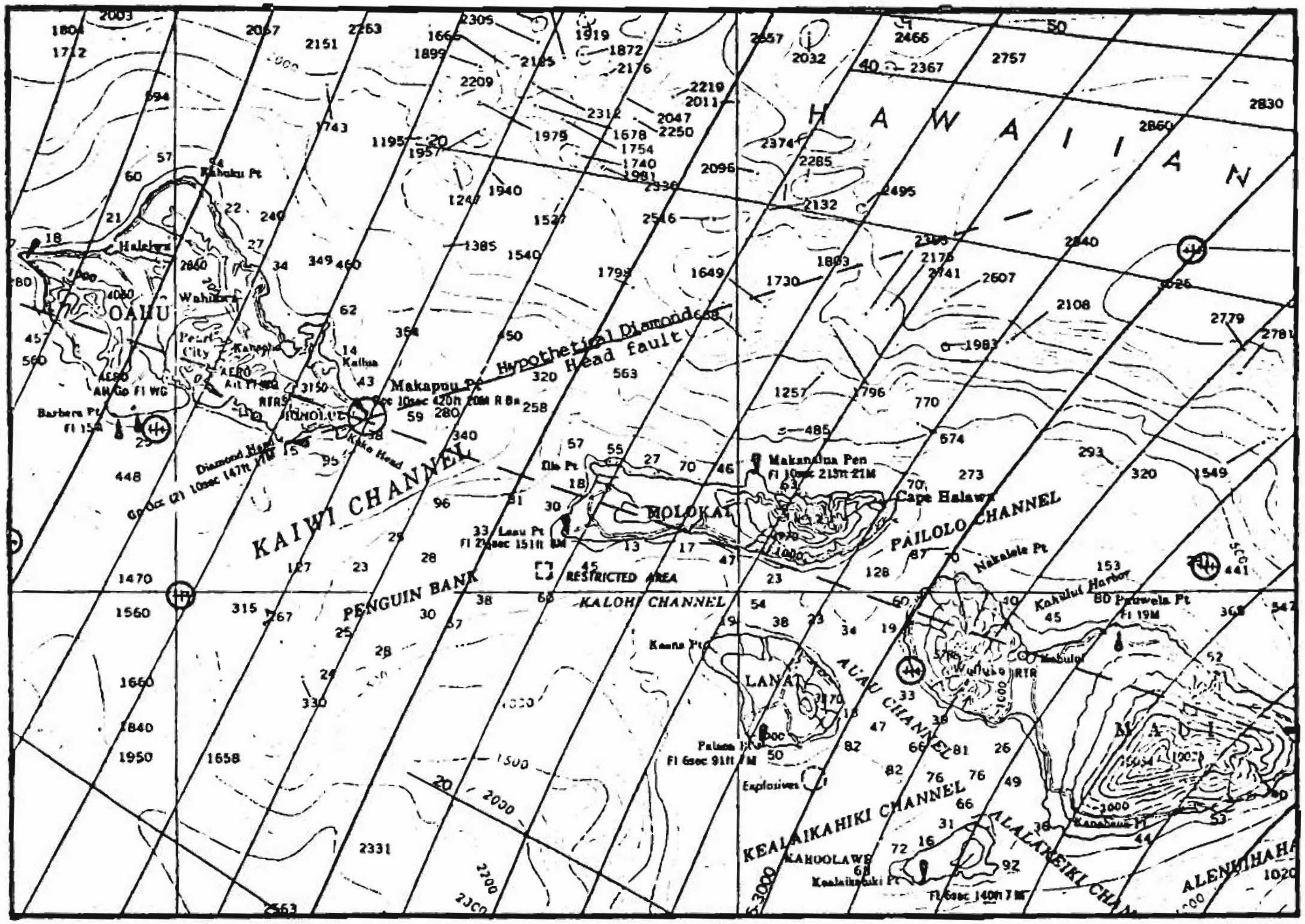

Figure 7. Bathymetry of the Oahu - Maui area.

Reproduced in figure 7 is a portion of Defense Mapping Agency chart 19009 on which the line of the DHf has been superimposed. It will be noted that the orientation of the deeper part of the Kaiwi Channel (that with depths greater than 300 fathoms) differs from the strike of the DHf by less than 10°. However, the axis of the channel is about 10 km south of the westerly part of the DHf, and there are no bathymetric lineaments corresponding to the easterly part of the DHf.

Summary

In summary, the existence of the Diamond Head fault, although suggested by the approximate alignment of the epicenters of several earthquakes, cannot be demonstrated conclusively by the combination of seismological, other geophysical, geological and bathymetric evidence.

Frequency distributions of earthquakes originating along the possible fault

Frequency distribution of magnitudes

As has long been recognized (Gutenberg and Richter, 1949), regional frequency distributions of earthquake magnitudes have the exponential form:

$$F_M = \exp\,(a'_M + b'_M M) \qquad (1a)$$

where M = magnitude

F_M = exceedence frequency of magnitude M

or, as more commonly expressed;

$$\ln F_M = a_M + b_M M \qquad (1b)$$

where $a_M = a'_M/\log e$

$b_M = b'_M/\log e$

Values of the intercept coefficients, a_M and a'_M vary greatly from region to region, but the slope coefficients, b_M and b'_M are approximate general constants. For the average of b_M, the value 1.0 is commonly used; the value 0.9 is suggested by the work of Gutenberg and Richter (1949) and used by Culver et al (1975); and the value 0.95 has been derived by Shi and Bolt (1982). Equivalent values of b'_M are 2.3, 2.1, and 2.0, respectively.

The 20-year period from 1962 through 1981 is too short, too few earthquakes occurred during it along the DHf, and the magnitude range of those earthquakes is too limited, for the record of that period to serve as a reliable basis for the frequency distribution of the magnitudes of DHf quakes even if their temporal distribution were strictly random. It is, in addition uncertain whether the the two 1976 quakes listed in table 5 originated along the DHf, and, if so, what their magnitudes were.

There are even more uncertainties in the case of longer-period records that may be drawn from Table 5. However, maximum and minimum exceedence frequencies have been calculated for the magnitudes of the quakes occurring during three periods of record: i) the 125-year period of record from 1859 through 1983; the 74-year period of record from 1910 through 1983; and the 20-year period of record from 1962 through 1981.

The quakes of each period were listed in order of decreasing magnitude in two sets of tables. One set included only those quakes known to have originated along the DHf line; the other included, in addition, those quakes that might have originated along that line whose magnitudes equalled or exceeded the cutoff values of

5.3 for the 125-year period of record and 3.6 for the other three periods of record. Average exceedence frequencies were calculated for each quake in each table as $F = m/T_R$, where m = serial number of quake in the table, T_R = duration of period of record.

The results are plotted in figure B. A point representing a combination of magnitude and frequency appearing in a table of the first set alone is shown in the figure as representing a minimum possible value because it cannot be certain that the records of that set include all quakes with that combination occurring during the respective period. A point representing a combination appearing in a table of the second set alone is shown in the figure as representing a maximum possible value because the tables of that set include quakes that may not have originated on the DHf. A point representing a combination appearing in both of the tables for a period is shown without designation as representing a minimum possible or maximum possible value.

The straight line shown on the figure is that with the slope b_M = 2.1 fitted by eye to the points representing the quakes the quakes with magnitudes of 4 or less. The value of a_M for the line plotted is 6.2

The point least well fit by the line is that representing the magnitude 5.0 quake of 1981 plotted at the frequency suggested by the occurrence of that quake during the 20-year period, 0.5 per year. A line with the same slope passing through that point would, however, suggest exceedence frequencies for magnitudes of 4.2 or less that are considerably greater than the possible maxima indicated by the 20-year record or even the 74-year record. The distribution for the 20-year record would be fit best by a line with a slope coefficient of 1.2 or 1.3.

It is possible that the difference between the distribution suggested by the 20-year record and that suggested by the longer-period records might be accounted for by seismic-gap theory, according to which the temporal distribution of the earthquakes with the largest magnitude characteristic of a region is not random but quasi-periodic. It is seems that the occurrence of one of these largest quakes is preceded by a period of increasing frequency for quakes of lesser magnitude and followed by a period during which the frequency of such quakes tapers off again. With this temporal distribution, the frequency distribution suggested by the record of a period considerably shorter than the recurrence "period" of th;e largest quakes might be:

i) linear, as in the case of equation 1), but with a larger value of a_M than that suggested by a very-long-period record if the short period included one of the largest magnitude quakes, but with a smaller value of a_M otherwise; or

ii) curvelinear, with smaller values of b_M associated with the higher magnitudes than the constant value suggested by a very-long-period if the short period included one of the largest magnitude quakes, but with larger values of b_M associated with the higher magnitudes otherwise.

With the second possibility, the small value of b_M suggested by thke 20-year record might be accoundted for by the quasi-periodicity of magnitude 5 quakes on the LDHf and the occurrence of the 1981 quake of that magnitude during the 20-year period. The recurrence "period" for magnitude 5 quakes suggested by the longer-period records is about 62 years; at present (in 1986) only 5 years have elapsed since the occurrence of one of those quakes on the DHf; and, hence, with respect to quakes of that magnitude there is at present no seismic gap on the DHf.

The frequency distribution provides no evidence for or against the existence of a seismic gap with respect to quakes of higher magnitude.

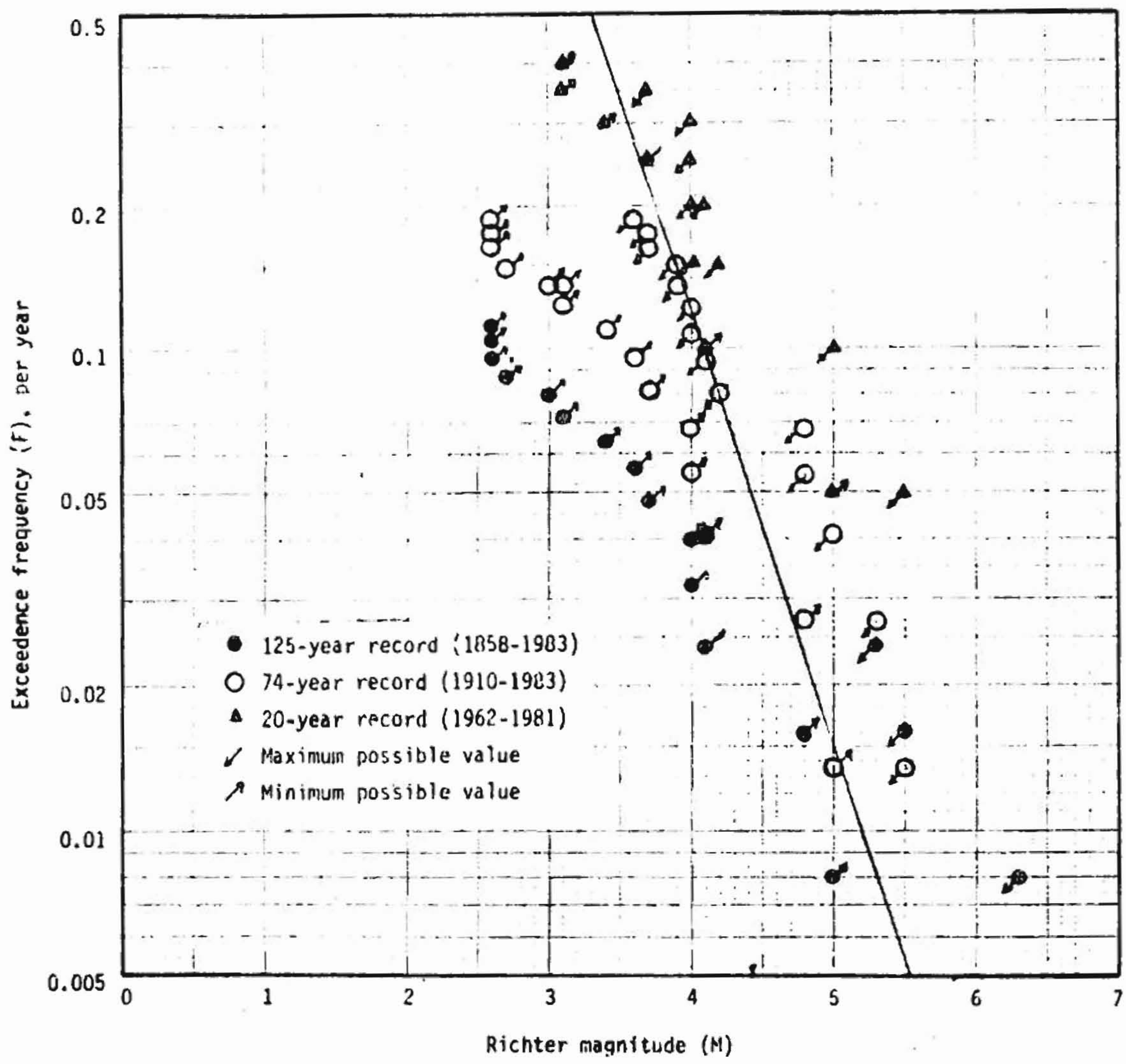

Figure 8. Frequency distribution of magnitudes of earthquakes originating along the hypothetical Diamond Head fault.

Frequency distribution of Honolulu intensities

Exceedence frequencies the average Honolulu intensities of the earthquakes originating or possibly originating along the OHf calculated in the same way as the exceedence frequencies of their magnitudes, are plotted in figure 9 assuming completeness of the 125-year record with respect to intensities (I') of 4.5 or greater and the shorter-period records with respect to intensities of 3.5 or greater.

In the general study of the earthquakes felt on Oahu, Cox (in press a) finds that the frequency distribution of their Honolulu intensities could be fit well by either a distribution of exponential form, such as would plot as a straight line on semi-log paper such as that used in figure 9, or one of power-law form, which would plot as a straigt line on log-log paper. In the case of the distribution of exponential form, expressed as:

$$\ln F_{I'} = a_{I'} + b_{I'} \cdot I' \qquad 2)$$

he found for the slope coefficient the value $b_{I'} = 1.38$. Cox (in press b) shows that frequency distributions of place-specific intensities generally should be fit well by either of the two forms, that the slopes of the distribution of either form at different places should be similar, and that the slope for the distribution of exponential form should be about 1.33.

The straight line shown, is that which, with a slope $b_{I'} = 1.38$, seemed best fit by eye to the distribution. The intercept, intercept $a_{I'} = 2.8$. The point least well fit is again that representing the magnitude 5.0 quake of 1981, which had a Honolulu intensity of 5.0, plotted with the minimum frequency of 0.5 per year suggested by the 20-year record. A line with a flatter slope would fit the distribution somewhat better, but neither the general improvement nor the fit to the point representing the 1981 quake would be significant.

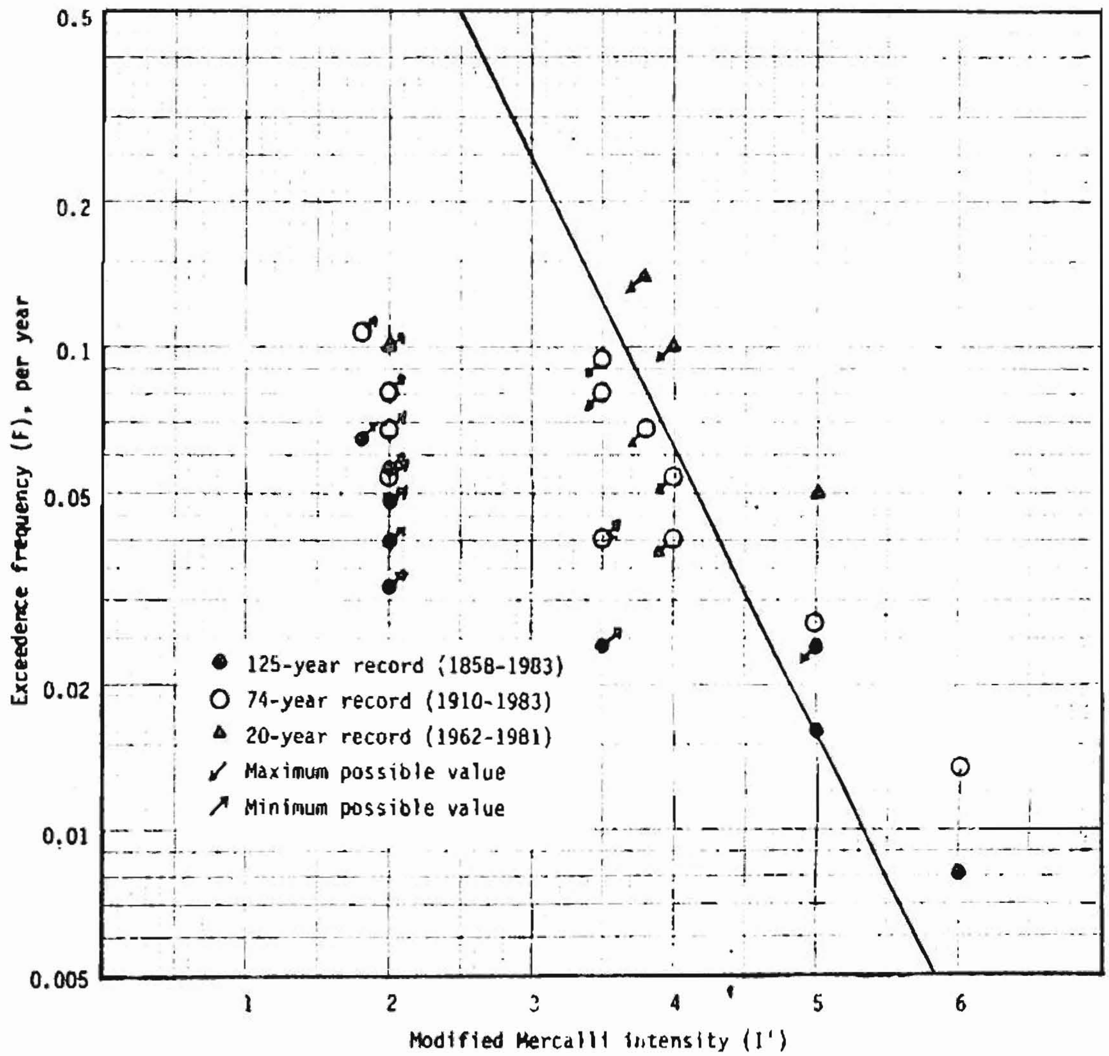

Figure 9. Frequency distribution of Honolulu intensities of earthquakes originating along the hypothetical Diamond Head fault.

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